NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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No. 1166

FUNDAMENTALS OF THE CONTROL OF GAS-TURBINE POWER PLANTS FOR AIRCRAFT

PART III
CONTROL OF JET ENGINES

By H. Kühl

Translation

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Control of Jet[1] Engines*

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SUMMARY

The basic principles of the control of TL[1] engines are developed on the basis of a quantitative investigation of the behavior of these engines under various operating conditions with particular consideration of the simplifications permissible in each case. Various possible means of control of jet engines are suggested and are illustrated by schematic designs.

I. BEHAVIOR OF JET POWER PLANTS UNDER VARIOUS OPERATING CONDITIONS

In part II of the report of these investigations (reference 1), systems were described for the direct limitation of the fuel quantity for the purpose of preventing an overstepping of the maximum permissible gas temperature ahead of the turbine or of the maximum speed, as well as avoiding the unstable region of the compressor operating range; general principles were derived for the control of the adjustable parts, in this case the jet-nozzle flow area. However, a final

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*"Grundlagen der Regelung von Gasturbinentriebwerken für Flugzeuge. Teil III - Regelung von TL-Triebwerken." Deutsche Luftfahrtforschung, Forschungsbericht Nr. 1796/3. Deutsche Versuchsanstalt f. Luftfahrt E. V., Inst. f. motorische Arbeitsverfahren und Thermodynamik, Berlin-Adlershof, ZWB, July 22, 1943.

[1]NACA comment: TL, jet.

determination of suitable regulating systems is possible only on the basis of an exact quantitative investigation of the behavior of the engines under various operating conditions.

A jet engine is shown schematically in figure 1 of part II of this report (reference 1). In order to obtain results as generally valid as possible, at first no particular compressor or turbine was used as the basis of the investigation; instead, computations were made for various pressure ratios of the compressor assuming constant efficiencies of the compressor and the turbine. Because in a given engine the pressure ratio of the compressor depends upon its characteristics diagram and the efficiencies of the compressor and the turbine vary with different operating conditions, by this method no exact numerical values are obtained for a particular engine but, on the other hand, a very good over-all view is obtained of the behavior of power plants of different designs under various operating conditions. Because the effect of the various influences is also approximately known, it is possible in most cases to suggest the definite design of the regulating system for a particular power plant; furthermore, it can be seen whether and in what direction further simplifications may be made in the case of particular properties under certain circumstances on the basis of special characteristics. For the exact determination of individual parts of the control device (gear ratios, control curves, etc.), it will, of course, be necessary to make use of the specific data.

If the compressor-characteristics diagram given as figure 2 in part II is used to check the simplifying assumption that the compressor efficiency is constant, it is found that for this compressor the variations in efficiency are actually unimportant. A more exact theoretical investigation of a turbine shows, furthermore, that for a particular machine the turbine efficiency η^*_t varies only a little if the following definition of turbine efficiency is used:

$$\eta^*_t = \frac{L_t}{L_{t\text{-}ad} - L_{ta}} = \frac{L_t}{L_{t\text{-}ad\text{-}st}}$$

where L_t is the useful work, $L_{t\text{-}ad}$ the work of adiabatic expansion from the pressure p_3 (based on the gas at rest) ahead of the turbine to the pressure p_4 (static pressure) behind the turbine, L_{ta} the useful energy of the gases at the discharge of the turbine, and $L_{t\text{-}ad\text{-}st}$ the work of adiabatic expansion from p_3 to the impact pressure p_{4st} behind the turbine per kilogram of gas.

The behavior of the power plant is essentially determined by the product of the compressor and the turbine efficiencies $\eta_l \eta^*_t$. In order to determine the influence of the absolute values of the efficiencies, the computation was made for two different turbine efficiencies. The details of the assumptions made are as follows:

Compressor efficiency based on the adiabatic curve . . . . η_l = 85 percent
Turbine efficiency based on the adiabatic curve[2]
  figures 1, 2, and 4 . . . . η^*_t = 70 percent
  figure 3 . . . . η^*_t = 80 percent
Efficiency of the impact scoop . . . . η_{st} = 90 percent
Efficiency of the combustion chamber . . . . η_b = 95 percent
Discharge coefficient of the turbine nozzle . . . . μ_t = 94 percent
Velocity coefficient of the jet nozzle . . . . φ_d = 96 percent
Pressure drop in the combustion chamber disregarded . . . . $p_3 = p_2$
Air for cooling the turbine blades is not taken into account.[3]

In order to investigate the influence of flight speed, computations were made for four different flight speeds corresponding to Mach numbers of 0, 0.307, 0.632, and 0.920 (flight speeds of 0, 100, 200, and 280 m/sec at a temperature ahead of the compressor of $T_1 = 269^\circ$ K, corresponding to 6 km Ina [NACA comment: International standard atmosphere] at 200 m/sec). The relation of the specific fuel consumption to the jet thrust for these four Mach numbers and for various parameters, pressure ratios in the compressor p_2/p_1, and the ratio of the gas temperature ahead of the turbine T_3 to the atmospheric temperature T_0 is shown in figure 1. In order to obtain a representation valid for all atmospheric pressures p_0

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[2]The value of 70 percent for η^*_t is obtained on the assumption that the turbine is designed with the smallest possible dimensions (small rotor diameter, very high exit velocity) and corresponds to only the efficiencies obtained in exhaust-gas turbines. With more favorable design, substantially higher values could be expected. The effect of this unfavorable assumption concerning the turbine efficiency on the calculated performance of the power plant will be canceled by the very favorable assumption concerning the compressor efficiency.

[3]The power cost of this cooling is accounted for in the turbine-efficiency coefficient. The quantity of cooling air requires a corresponding enlargement of the jet-nozzle flow area. The variation of the jet-nozzle flow area under different operating conditions, which alone is of interest here, would not be substantially affected thereby.

and temperatures T_o, the individual quantities were expressed in terms of the characteristic values derived by the laws of similarity (reference 2): namely, Mach number $Ma_o = w_o/\sqrt{g\kappa_L R_L T_o}$ for the flight speed, the thrust coefficient $\sigma = S/F_t p_o$, the thrust per unit of turbine-nozzle flow area when atmospheric pressure is 1 atmosphere for the thrust, and the characteristic $b_S\sqrt{250/T_o}$ for the specific fuel consumption b_S. The values along the ordinate thus directly represent the specific fuel consumption (g/kg sec thrust) for an atmospheric temperature of 250° K (about 6 km Ina). For other temperatures T_o, these values must be multiplied by $\sqrt{T_o/250}$ to obtain the specific fuel consumption.

The curves of p_2/p_1 = constant have not been drawn in but have been indicated by the inserted numbers to avoid confusing appearance. For a particular power plant, it would be better to use the characteristic value $n/\sqrt{T_1}$, which is primarily dependent upon the speed n (or some other characteristic value that is proportional to the Mach number of the compressor tip speed) instead of the pressure ratio p_2/p_1. A constant value of $n/\sqrt{T_1}$ in the presence of a decreasing temperature ratio T_3/T_o corresponds to a diminishing pressure ratio p_2/p_1; the numerical relation between $n/\sqrt{T_1}$ and p_2/p_1 depends upon the characteristics diagram of the compressor.

If in figure 1 an envelope curve is drawn around the individual curves T_3/T_o = constant, this curve represents at each point the most favorable setting in respect to fuel consumption for the respective output (thrust coefficient). With a suitable design of the power plant, as will be evident from considerations subsequently set forth, the design point will probably always lie somewhat above this envelope curve; this position will be more pronounced, the higher the gas temperature T_3 ahead of the turbine.

By consideration first of the maximum obtainable output, it is observed at once that maximum output will be attained at every moment that the temperature ratio T_3/T_o and the pressure ratio p_2/p_1, which is for a specific speed, are as large as possible.

In the operating region in question and at a given pressure ratio, an increase of the gas temperature T_3 and therefore of the temperature ratio T_3/T_o involves in many cases a slight increase in the specific fuel consumption at full power; but the effect of the increase on the over-all fuel consumption is very favorable as the specific fuel consumption at partial load is thereby lowered.

For a specific power plant, the maximum permissible temperature ratio T_3/T_0 varies with the atmospheric temperature because a limit is set to T_3. The maximum pressure ratio is determined from the compressor-characteristic curves for T_{3max} and n_{max}; it is a function of the temperature T_1 and hence equally of T_0. For example, if at a flight speed corresponding to $Ma_0 = 0.632$, the atmospheric temperature changes from 15° to -56.5° C (0 to 11 km Ina) and if $t_3 = 800°$ C and the compressor characteristics are as shown in figure 2 of part II, an increase of about 35 percent in the pressure ratio p_2/p_1 will occur and the thrust coefficient σ will be almost doubled (fig. 4). It is thus evident that the jet thrust of a power plant is markedly affected by the atmospheric temperature.

The adjustment of a specific power plant for operation at lower output, that is, at a lower thrust coefficient σ, may be accomplished by the reduction either of the temperature ratio T_3/T_0 or the pressure ratio p_2/p_1. From figure 1 it can be seen at once that, taking full-power setting as the point of departure, at each moment the most favorable specific fuel consumption will be obtained if only the temperature ratio T_3/T_0 is decreased until the envelope curve is reached while the pressure ratio p_2/p_1 is kept as high as possible, that is, the speed is maintained constant at its maximum value. Even though the speed is kept constant, there will be, according to the compressor-characteristics diagram, a certain decrease in the pressure ratio.

II. CONCLUSIONS FOR CONTROL OF JET-NOZZLE FLOW AREA

Every operating point in the graphs of figure 1 corresponds to a definite flow area of the jet nozzle and to a definite characteristic value for the fuel quantity B per unit of time. (See part I.) Regardless of whether the fuel control is effectuated indirectly or directly by means of the pilot's manual control lever, every variation of the quantity of fuel supplied within the permissible limits serves in effect to regulate the output (thrust coefficient) of the engine. The jet-nozzle flow area must be so controlled that at partial load the highest possible utilization of the fuel is obtained and at full-power setting the highest possible output.

From the investigations of the behavior of the power plant under various operating conditions, the following requirements for a system of control may be derived: In the region of higher output, the speed is to be held constant at first. This speed will also make possible the attainment of the maximum output at each moment under the respective external operating conditions (T_o, p_o, w_o). With decreasing output, the speed is to be kept constant until the envelope curve is reached. If the output is to be decreased further, the operating condition corresponding to the envelope curve is to be effectuated insofar as possible.

The question now is how the jet-nozzle flow area must be varied to accomplish the required regulation.[4] Figure 2 shows the variation of the jet-nozzle flow area for the various operating conditions. The required flow areas, expressed as the ratio of jet-nozzle flow area F_d to turbine-nozzle flow area F_t, are plotted against thrust coefficient σ for various pressure ratios p_2/p_1 and temperature ratios T_3/T_o. It is evident that the required jet-nozzle flow area increases with an increase in the pressure ratio p_2/p_1 and also with a decrease in the temperature ratio T_3/T_o.

In order to demonstrate at the same time how the specific fuel consumption is affected by the jet-nozzle flow area, the curves of constant increase of specific fuel consumption b_S above the optimum value b_{Smin} at a given thrust coefficient, expressed as the ratio b_S/b_{Smin}, are plotted in figure 2 as dot-dashed lines. The envelope curves in figure 1 would correspond to the curve for $b_S/b_{Smin} = 1$, which is not plotted here as its determination would be too inexact.[5] The jet-nozzle flow area corresponding to optimum fuel consumption increases with increasing pressure ratio p_2/p_1 and with decreasing flight speed. This jet-nozzle flow area is a function of two characteristic values such as p_2/p_1 and Ma_o, as has already been shown (section III, part II) on the basis of general considerations.

The numerical values in figures 1 and 2 were obtained on the assumption of certain constant values for the component efficiency coefficients among which the product of compressor and turbine efficiencies is of primary importance. In order to show that the essential conclusions may nevertheless be generalized, the same computations

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[4]There are no other parts of the jet engine the regulation of which appears useful. Regulation of the turbine-nozzle area, quite aside from its cost, would obviously produce no substantial advantage in this engine.

[5]Naturally, the other b_S/b_{Smin} = constant curves are also only approximate because even very slight errors such as are especially unavoidable in the plotting of envelope curves, introduce rather marked displacements of the b_S/b_{Smin} = constant curves.

were also made for the Mach number $Ma_o = 0.632$ with a higher value for the turbine efficiency. A recomputation for various Mach numbers was unnecessary in this case because the influence, as a simple estimate showed, is always substantially the same. The results of the computation are shown in figure 3. The individual curves follow essentially the same course as in figures 1 and 2. The conclusions derived from figures 1 and 2 may therefore be accorded general validity.

For a specific power plant, the dependence of the various values upon the pressure ratio is generally of less interest than the dependence upon speed because in a specific power plant it is generally the speed that is given. In order to show an example of the relations that result, the curves for $(n/\sqrt{T_1})\sqrt{T_{1n}}/n_n$ = constant (that is, $n/\sqrt{T_1}$ = constant), as derived from the pressure curves of the compressor-characteristics diagram in figure 2 of part II have been plotted in figure 4 instead of the curves of p_2/p_1 = constant (fig. 2).

With the type of control in question, taken from the full-power setting, the jet-nozzle flow area increases with a decreasing thrust coefficient as long as the speed is held constant, that is, theoretically, until the curve $b_S/b_{Smin} = 1$ is reached. With a further decrease of the thrust, control should be governed by the curve $b_S/b_{Smin} = 1$ or according to the envelope curve in figure 1. In practice the effort will naturally be made to use as simple arrangements as possible for control in this second region in which theoretically the jet-nozzle flow area depends on p_2/p_1, or on $n\sqrt{T_1}$ and Ma_o (that is, p_1/p_o). Inexact control here involves only an increase of the specific fuel consumption; it cannot involve damage to the engine.

The extent of the region in which control to secure optimum fuel consumption is of practical importance is decisive in determining the simplifications that are permissible. The lowest flight speed at which fuel consumption is important is the flight speed having the lowest fuel consumption per unit of time (cruising, climbing). Although the lowest flight speed at which the aircraft will remain capable of flight without assisted take-off will remain for take-off and landing purposes in the same range (about 250 km/hr); as for other types of high-speed aircraft, the flight speed with the lowest fuel consumption per unit time (also the speed for greatest flight radius) for the jet engine nevertheless is substantially higher than for corresponding aircraft with Otto engines because in the jet engine the specific fuel consumption calculated on the thrust power increases very markedly with decreasing flight speed. Therefore the speed having the lowest fuel consumption per unit of time will lie somewhat below 100 meters per second ($Ma_o = 0.3$) only at very low altitudes; at higher altitudes this speed will be greater.

Because, on the other hand, jet engines are primarily intended for very high-speed aircraft, the range of speed and hence of thrust coefficient[6], which must be considered, is nevertheless very large and it may be taken for granted that the minimum value of the thrust coefficient, at which control to produce minimum fuel consumption is of importance, may be as low as about 25 percent of the value at maximum speed and normal (Ina) temperature.

First, a simplification of the control system is possible if in the region where control is governed by $b_{S_{min}}$ the Mach number Ma_o is considered. In the investigation of such a control system, it will suffice, in view of the considerations just discussed, to deal with the Mach numbers 0.307, 0.632, and 0.92 for which the results of computations are already available.

For ready visualization, the jet-nozzle flow areas, expressed as F_d/F_t, at which the increase of specific fuel consumption above the optimum value amounts to 2 percent ($b_S/b_{S_{min}} = 1.02$) and plotted as a function of the pressure ratio are given in figure 5(a) for these Mach numbers. In the region between the two curves, for each Mach number the increase of specific fuel consumption remains at all times less than 2 percent. Figure 5(b) gives the same data using the value of $(n/\sqrt{T_1})\sqrt{T_{1n}}/n_n$ from figure 4 as the abscissa. Evidently the variation due to different Mach numbers, as compared with the distance between the two curves for any one Mach number, becomes smaller and smaller as the pressure ratio or the speed so increases that control of the jet-nozzle flow area in accordance with a mean curve dependent on p_2/p_1 or $n/\sqrt{T_1}$ will satisfy even the highest requirements for accuracy of regulation. A certain overlapping of the individual curves occurs at pressure ratios less than about $p_2/p_1 = 2$ but in reality the higher Mach numbers are then practically eliminated because at the lower pressure ratios the aircraft can no longer attain the higher speeds except in the here unimportant case of gliding flight. Therefore, the control of F_d/F_t as a function of p_2/p_1 or $n/\sqrt{T_1}$ even in this region will be entirely satisfactory as to accuracy.

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[6]In horizontal flight, the thrust coefficient for a specific aircraft is proportional to the product of the coefficient of resistance of the aircraft and the square of the Mach number Ma_o of the speed.

In general, the quantity $n/\sqrt{T_1}$ can more easily be made to control the regulator than can the pressure ratio p_2/p_1. Because, as may be seen from figure 5, a very great exactness of control is unnecessary, it will suffice to take account of the temperature additively, that is, to consider the expression $n/\sqrt{T_1}$ as approximately proportional to the expression $(n - CT_1)$ (C being a constant).

In many cases, especially at high gas temperatures, a further simplification may be attained without any serious increase in the fuel consumption by simply not taking any account of the temperature T_1.

Finally, many cases will occur in which it will prove permissible to leave the jet-nozzle flow area unchanged in the region where control would be governed by $b_{S_{min}}$. In the example given in figure 4, a very good fuel utilization is still obtained with an upper limit to the jet-nozzle flow area approximately equivalent to $F_d/F_t = 2$, if the assumption is made that the smallest thrust coefficient σ at which the fuel consumption is important is about 0.5 at $Ma_o = 0.307$ and $Ma_o = 0.632$; (it is substantially larger when $Ma_o = 0.92$). The specific fuel consumption thus attained is, at the most unfavorable operating points, not much more than 2 percent higher than in a more exact control system.

The errors that occur with these simplified methods of control are, of course, different for various power plants; therefore, each case must be individually computed to determine if simplified control is appropriate.

III. METHODS OF LIMITATION OF FUEL QUANTITY

In addition to the arrangements for the regulation of the jet-nozzle flow area, the arrangements for the control of the fuel supply must be considered. Generally applicable types of design for these devices were described in section II of part II.

If only a limitation of the gas temperature T_3 ahead of the turbine when operating at equilibrium condition[7] is required and if no consideration need be given to the unstable region of compressor

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[7]During acceleration, a too rapid increase of the fuel quantity supplied may be prevented by simple auxiliary devices attached to the valve rods.

operation (and under other assumptions to be subsequently described), instead of the arrangements for the limitation of the fuel quantity previously described in many cases another system may be employed in which a limitation of the gas temperature T_3 is accomplished in a simple manner in combination with the control of the jet nozzle.

The jet-nozzle flow area of a specific power plant at maximum speed and maximum gas temperature is, as previously shown in section III of part II, generally a function of the temperature T_1 ahead of the compressor and of the pressure ratio p_1/p_0 (corresponding to Ma_0). In figure 4 are shown the curves for constant speed $n = n_n$ and constant combustion temperature $t_3 = 800^\circ$ C; the temperatures T_1 and T_0 are indicated by the numbers written in. The almost horizontal course of the right-hand part of this curve is caused by the peculiarities of the compressor-characteristics diagrams that were used as the basis of the computation. If the slope of the pressure curves in the compressor-characteristics diagram had been steeper, the curves of $(n/\sqrt{T_1})\sqrt{T_{1m}}/n_n$ = constant would ascend more steeply from left to right.

Whereas at low temperatures T_1 the values of F_d/F_t for different Mach numbers in figure 4 are practically the same, at higher temperatures an increase of F_d/F_t occurs with a decrease in Mach number. This independence of the Mach number Ma_0 at lower temperatures is due to the fact that in this region the critical velocity is reached in the jet nozzle. In this case, the pressure behind the turbine and hence the operating condition of the compressor and the turbine are dependent upon only the condition ahead of the compressor, whereas the atmospheric pressure does not directly influence the processes occurring in the compressor and the turbine. In this region, the jet-nozzle flow area is dependent upon only the temperature ahead of the compressor.

The extent of this region depends upon the design of the power plant. If the compressor has a large pressure head and if the gas temperature ahead of the turbine is high, the Mach number can remain without influence throughout the whole range of T_1; the influence of the Mach number becomes greater in proportion as the pressure head of the compressor is smaller and the gas temperature T_3 is lower.

In the example illustrated in figure 4, disregard of the Mach number at the highest atmospheric temperatures would lead at once to a marked reduction of output. That is, if the jet-nozzle flow area is set larger than the exact theoretical area, an operating condition is brought about, which has a smaller value of T_3/T_0 than precise control would have produced, if the speed is held constant, and therefore a correspondingly smaller output is obtained. If the area actually set up is smaller than the theoretical area for precise control, at a given speed a higher gas temperature T_3 is produced than precise control would call for. Because this excess temperature must be prevented, the control would have to effectuate at each moment the maximum flow area corresponding to the respective temperature T_1, that is, in this case the flow area corresponding to a Mach number of zero. With this setting, when the Mach number is actually larger, a considerable reduction of thrust at the highest atmospheric temperatures is obtained, that is, precisely where the thrust tends to be relatively small and where a further reduction is therefore particularly undesirable.

In spite of the fact that the influence of the Mach number on the jet-nozzle flow area is not extremely great, in the case under consideration a purpose would be served by consideration of the Mach number, that is, of the pressure ratio p_1/p_o; however, an approximate evaluation of p_1/p_o will suffice. Because the influence of the pressure ratio p_1/p_o is substantially felt only at higher atmospheric temperatures, which are at the lower altitudes and consequent higher pressures p_o, in the example shown in figure 4 the pressure ratio p_1/p_o may be replaced by an approximation, namely the pressure difference $p_1 - p_o$.

A disadvantage of all systems involving limitation of the fuel quantity as a function of the jet-nozzle flow area consists of the relatively small differences among the flow areas that correspond to various gas temperatures. A change in jet-nozzle flow area of 1 percent corresponds to a change in the gas temperature T_3, which from figure 4 amounts to approximately 20 to 30 percent and would amount to considerably more in other compressors for which the pressure lines follow a steeper slope in the characteristics diagram and for which the efficiency drops markedly with an increase of the temperature ratio T_3/T_1. In short, the maximum gas temperature in the engine T_{3max} is strongly affected even by slight movements of the jet nozzle and therefore in many cases an accurate prediction cannot be made as to whether such a control system would work well in practice. The use of this system becomes impossible when the $n/\sqrt{T_1}$ curves in the graph of F_d/F_t plotted against σ (fig. 4) are horizontal or exhibit a minimum at any point.

IV. SUGGESTED DESIGNS FOR CONTROL OF JET ENGINES

An example of a design of a system for controlling the jet-nozzle flow area, the control being of the type in which the pilot's manual control lever directly sets the fuel quantity, is shown in figure 6. There the assumption is made that in the region where $b_S/b_{S\,min} = 1$ should govern, the jet-nozzle flow area is controlled as a function of $n/\sqrt{T_1}$, in which T_1 is only approximately determined. The changes that would be made to produce a simplified control system (see p. 8 f.) are stated in the legend of this figure.

In the region of higher output where the speed is to be held constant by the control, the jet-nozzle flow area is controlled by the governor a, which actuates the valve piston d of the servomotor through the bell crank b and the return lever c. With decreasing output, the flow area of the jet nozzle f is increased by the action of the working piston e of the servomotor. As the flow area increases, the lower part of the return lever c comes to rest on the cam plate g. If the output is further decreased through a reduction in the quantity of fuel supplied, the bell crank b rises from the return lever c and the control of the jet-nozzle flow area is accomplished by the cam plate g. The cam plate is fastened to the lever i, which is turned by the governor a through the rod h. In order to provide an approximate response to the value of the temperature T_1 in the expression $n/\sqrt{T_1}$, the right-hand pivot of the lever i is displaced by the thermocouple (bimetallic strip) k in accordance with T_1.

The control arrangement shown in figure 6 controls only the jet-nozzle flow area. In addition, the arrangements discussed in section II of part II for the selection and limitation of the fuel quantity, corresponding to figures 5 or 8 of part II, are necessary.

If with constant speed the variation of the jet-nozzle flow area is sufficiently great and if a limitation of the gas temperature during acceleration and special means for avoiding the unstable region of compressor operation are unnecessary, then as already shown it is also possible to limit the fuel quantity in a simple manner in combination with the control of the jet-nozzle flow area.

Such a control system is schematically shown in figure 7. The arrangements for control of the jet-nozzle flow area are the same here as in figure 6. The quantity of fuel supplied is controlled by the overflow valve m, located downstream of the fuel pump l and connected to the pilot's manual control lever n. If at any moment the jet-nozzle flow area exceeds the limiting values, dependent upon T_1 and p_1/p_o, at which the maximum speed and maximum permissible gas temperature occur, a second overflow valve p in the fuel line is opened by the lever o and the fuel quantity is thereby limited. The response to the temperature T_1 and the pressure ratio p_1/p_o is produced by the cam surface q, which is revolved in accordance with T_1 (for example, by the thermocouple k through a system of rods not shown in the drawing) and displaced axially in accord with p_1/p_o. The device[8] r for inclusion of the pressure ratio p_1/p_o or, if that suffices, the pressure difference $p_1 - p_o$, is not shown in detail for simplicity. If the limiting value of the jet-nozzle flow area is also reached at low-power output, the lever o is turned by the intermediate lever s; otherwise, its movement is directly dependent upon the flow area. With the arrangement of the intermediate lever s shown in the figure, the limitation of the fuel quantity becomes operative only at maximum speed.

A substantially different system of control results if the movement of the pilot's manual control lever selects a value of the speed rather than of the fuel quantity. A regulating system of this kind is shown in figure 8. In this case the immediate effect of a movement of power lever a is to rotate the shaft b. By the action of the cam c connected to this shaft, the lever d, and the governor o, the speed is determined, inasmuch as when the selected speed is attained, the rod e attached to the lever d opens an overflow valve f between the fuel pump g and the injection nozzles h. The speed first rises with increasing output to its selected value and then remains constant. The control of the jet-nozzle flow area is accomplished through the cam surface i, which turns with the shaft b and is displaced axially by the thermocouple k in proportion to the temperature T_1 ahead of the compressor. In accordance with the displacement of the pin l, the jet-nozzle flow area is adjusted by the servomotor m, which is not shown in detail. In the region of varying speed, the flow area is controlled as a function of $n/\sqrt{T_1}$ approximately in accordance with the $b_S/b_{Smin} = 1$ curve. When the maximum speed is reached, the pilot's manual control lever is set for still higher power, the jet-nozzle flow area is reduced until the limiting value is reached. If it is necessary to take into account the influence of the pressure ratio p_1/p_o on the jet-nozzle flow area at maximum output, this adjustment can be done by means of an adjustable stop o that is moved in proportion

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[8]If it is unnecessary to consider the pressure ratio p_1/p_o, this device will, of course, be omitted.

to p_1/p_0, or if permissible $p_1 - p_0$ by the device p, not shown in detail. This adjustable stop limits the rotation of the cam surface i. If at constant speed the variation of the jet-nozzle flow area with the gas temperature T_3 is large enough and if a limitation of the fuel quantity governed by the gas temperature during acceleration and by the unstable operating region of the compressor is unnecessary, the arrangements q for the direct limitation of fuel quantity, described in section II of part II, which are inserted into the fuel line between the overflow valve and the injection nozzles, are not required. If these arrangements cannot be eliminated[9], the system shown in figure 6 would probably be preferred.

The question of whether the regulating systems discussed would require simple auxiliary devices for idling and starting was not investigated in detail because of lack of adequate evidence.

A rough estimate, which did not extend to the question of idling, shows that regions of unstable operation of the power plant will not appear when using the control systems previously described as long as the compressor operates in the stable region of its characteristics diagram.

In addition to the designs suggested here, of which that shown in figure 6 is probably the best for most cases, still other methods of control deserve consideration. However, the purpose of the present investigation is not to give an exhaustive presentation of all possible designs; rather, the purpose is to present, in addition to the description of several good designs, the basic principles on which the various possible designs may be evaluated. Therefore, only one more question shall be investigated, namely, whether alteration of the jet-nozzle flow area may be entirely eliminated under certain circumstances.

V. CONTROL IN CASE OF FIXED JET-NOZZLE FLOW AREA

Because, for the example illustrated in figure 4, at maximum output the jet-nozzle flow area changes very little under various operating conditions, it seems likely that variation of the flow area can be

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[9]A limitation of the jet-nozzle flow area at maximum output is necessary even in this case. However, the area limitation may under certain circumstances be combined with the devices for limitation of the fuel quantity in such a way that limitation of the flow area takes place when the overflow valve (f in fig. 3, part II), which forms part of those devices, is opened.

eliminated in such a case. A case in which a mean value equivalent to $F_d/F_t = 1.77$ is chosen for the fixed jet-nozzle flow area in this example will be considered first.

This control will result, as can be seen from figure 4, in differences in the specific fuel consumption in flight, compared with the values obtained with controlled flow area, of 7 percent at the maximum; on the average, however, these differences will be substantially smaller. The differences between the values obtained with exact control and those obtained with fixed nozzle flow area are thus considerable but in many cases supportable.

A more important question is, how the maximum obtainable output compares with that for variable nozzle flow area. When the controlled jet-nozzle flow area is less than the selected fixed jet-nozzle flow area, the operating condition for maximum output with fixed jet nozzle is obtained as follows: taken from the operating condition in the case of the controlled nozzle, at constant speed $(n/\sqrt{T_1}$ = constant or $(n/\sqrt{T_1})\sqrt{T_{1n}}/n_n$ = constant), the gas temperature T_3 and consequently the value of T_3/T_o is reduced to the point at which the operating condition corresponding to the fixed jet-nozzle flow area is reached. If the controlled jet-nozzle flow area is greater than the actual fixed jet-nozzle flow area, at constant gas temperature (T_3/T_o = constant) the speed is to be reduced to the value corresponding to the fixed jet-nozzle flow area.

The loss of power when using a fixed jet nozzle corresponds to the difference between the thrust coefficients σ for controlled and for fixed jet nozzles. For the example under consideration, the loss amounts to about 10 percent for the highest temperatures involved and for a Mach number Ma_o of 0.632; the loss is, however, much lower for the rest of the operating range. At a Mach number of 0.920, the difference would amount to 30 or 40 percent but this value is unimportant because so great a flight speed could occur at the highest temperature only in gliding flight in view of the marked reduction of output of the power plant at high atmospheric temperatures. The power losses calculated for the example under consideration appear to be quite supportable in many cases if the simplification is the decisive factor.

These conclusions apply, however, only to the example under consideration. That is, the increase of specific fuel consumption due to the fixed nozzle flow area would presumably be of the same order of magnitude for power plants of different design; the small reduction in maximum output, which has been calculated for this example, is due, on the other hand, to the particular qualities of the power plant in question and primarily to the flatness of the pressure lines in the compressor-characteristics diagram used as the basis of the computations. If these lines followed the steeper course, which is most usual today, the values of F_d/F_t for maximum output as expressed in figure 4 would, as already pointed out, rise with increasing thrust coefficient and the reduction in maximum output caused by a fixed jet-nozzle flow area would, especially at high and low temperatures T_o, became very much greater than in the example considered.

Accordingly, omission of control of the jet-nozzle flow area can no doubt be considered only in special cases and specifically in connection with compressors having very flat pressure lines in the characteristics diagram.

Gas-turbine power plants having a fixed jet-nozzle flow area require the same control devices for the limitation of the fuel quantity as previously described.

If in the case of the given power plant, at constant speed the variation of the controlled jet-nozzle flow area with the gas temperature is sufficiently great, and if in limiting the fuel quantity it is possible to disregard the gas temperature during acceleration and the unstable operating region of the compressor, it will suffice to insert between the fuel pump and the injection nozzles an overflow valve that will be opened at a certain speed dependent upon the operating condition. In the region in which the flow area of the fixed jet nozzle is greater than the flow area of a controlled jet nozzle for maximum output, as the fuel supply is increased maximum speed will be attained before maximum permissible gas temperature, therefore the overflow valve will not have to be opened until the maximum speed is reached. In the region in which the fixed jet-nozzle flow area is smaller than the controlled flow area for maximum output, the maximum permissible gas temperature will be reached at a lower speed. This speed, at which the overflow valve must be opened, is in general dependent on the temperature T_1 and the pressure ratio p_1/p_o.

Figure 9 shows the layout of such a control system. The movement of the pilot's manual control lever a selects the fuel quantity by means of the overflow valve b located in the fuel line between the fuel pump c and the injection nozzles d. A second overflow valve e is actuated by the governor g through the lever f. In order to obtain the desired dependence of the speed on T_1 and p_1/p_o when the pilot's manual control lever is set for maximum output, the fulcrum of the lever f is located on the rod h, which is actuated by the cam surface i. This cam surface i is rotated about the axis l by the thermocouple k (bimetallic strip) and (insofar as disregard of p_1/p_0 is impossible) displaced axially by the device m in proportion to p_1/p_0 or if permissible $p_1 - p_0$.

The variation of the speed at which the overflow valve is opened can be eliminated and thereby a further simplification of the regulating system secured if the fixed jet-nozzle flow area is made equal to the maximum jet-nozzle flow area that would be required for maximum output with a regulated jet nozzle; for in this case, under every operating condition the maximum speed will be reached before the maximum permissible gas temperature. In the example to which figure 4 applies, the required enlargement of the jet-nozzle flow area would not be very significant. Actually, the enlargement would involve a slight improvement in the specific fuel consumption. On the other hand, the drop in maximum output would generally be greater. At a Mach number Ma_0 of 0.632 and at high atmospheric temperatures, the drop as compared to an engine with jet nozzles would amount to about 15 percent instead of the 10 percent previously mentioned and even in the remainder of the range it would be on the average correspondingly higher than with a smaller jet-nozzle flow area. It is certainly possible to conceive of cases in which even such a loss of power would be supportable.

Here again generalizations cannot be made from the numerical results. With compressors, the pressure lines of which run more steeply, a substantially greater power drop is to be expected.

SUMMARY

In order to obtain more exact data on which to base systems of control for jet power plants, the behavior of these engines under various operating conditions was first investigated. For various Mach numbers of flight speed, various pressure ratios in the compressor, and various ratios of combustion temperature to atmospheric temperature, the characteristic values of the specific fuel consumption (fuel consumption multiplied by square root of atmospheric temperature), the thrust coefficients (thrust per unit of turbine-nozzle flow area at a pressure of 1 atm), and the corresponding flow areas of the jet nozzle (expressed as the ratio of jet-nozzle flow area to turbine-nozzle flow area) were computed. By the use of these values, a representation independent of atmospheric pressure and temperature is obtained.

The theoretical investigations show that for the realization of the maximum possible output and the attainment of the highest possible

fuel utilization, the jet-nozzle flow area must be so controlled in the region of higher output that the speed remains constant whereas at lesser output it should, in general, be governed by the pressure ratio in the compressor or, more simply, by the quotient of speed divided by the square root of absolute temperature ahead of the compressor. If this region is small, in many cases regulation based on the speed will suffice here also. In fact, it is often possible to keep the jet-nozzle flow area constant in the region in which the speed may vary and thus achieve a further simplification of the control system without incurring any increase in specific fuel consumption that would have serious effect in practice.

In addition to the arrangements for the control of the jet-nozzle flow area, arrangements for the control and limitation of the fuel quantity are considered. Such arrangements were suggested and discussed in section II, part II. If no more is required than the limitation of the fuel quantity when the maximum permissible gas temperature ahead of the turbine is reached in equilibrium condition and if at constant speed the variation of the jet-nozzle flow area as governed by the combustion temperature is sufficiently large, it is also possible, as is set forth in detail, to effect the limitation of the fuel quantity in a simple manner in combination with control of the jet-nozzle flow area.

Various possible methods of control for jet engines are visualized through schematic designs. Presumably, the system shown in figure 6 for the control of the jet-nozzle flow area plus the arrangements described in part II for the regulation of the fuel quantity will be preferable in most cases.

Finally, an investigation of the behavior of jet engines with fixed jet-nozzle flow area shows that in exceptional cases, especially with compressors having very flat pressure lines in the characteristics, the increase in specific fuel consumption and the reduction of power output, even under extreme operating conditions, may remain within such limits as to be supportable in the case of engines in the design of which the requirement of simplicity outweighs the need of full exploitation of the given possibilities. In the general case, however, control of the jet-nozzle flow area cannot be eliminated.

Translation by Edward S. Shafer,
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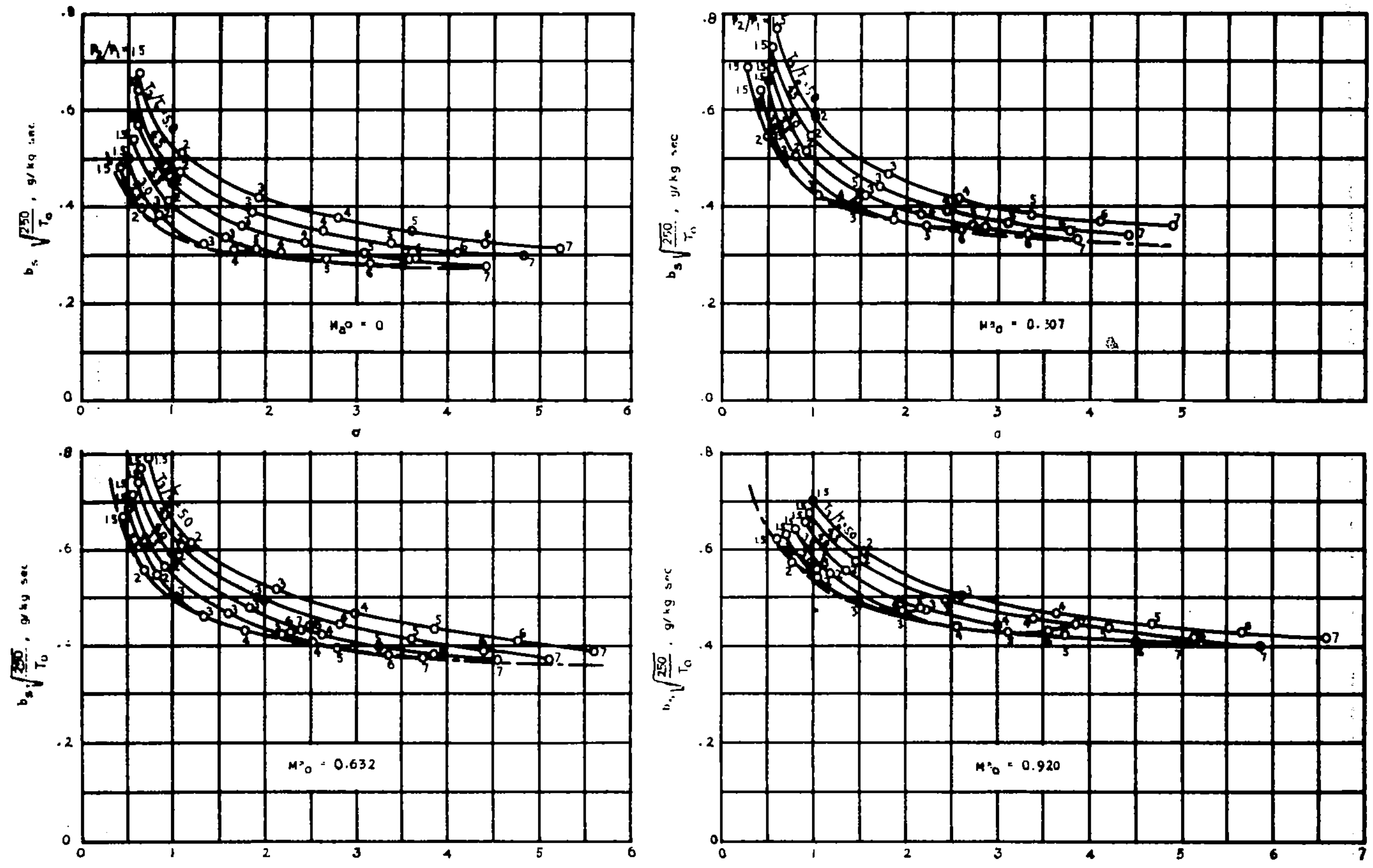

Figure 1. - Index of specific fuel consumption $b_S\sqrt{250/T_0}$ as function of thrust coefficient $\sigma = S/F_t p_0$ plotted for four Mach numbers $Ma_0 = w_0/20.1\sqrt{T_0}$ calculated on flight speeds (w_0 in m/sec) for various pressure ratios p_2/p_1 (inserted numbers) and temperature ratios T_3/T_0.

Product of compressor and turbine efficiencies $\eta_l \; \eta^*_t = 0.595$;

$\eta_l = 0.85$; $\eta^*_t = 0.70$; $\eta_{st} = 0.90$; $\eta_b = 0.95$; $\mu_t = 0.94$:

$\varphi_d = 0.96$; $p_3 = p_2$

Fig. 2

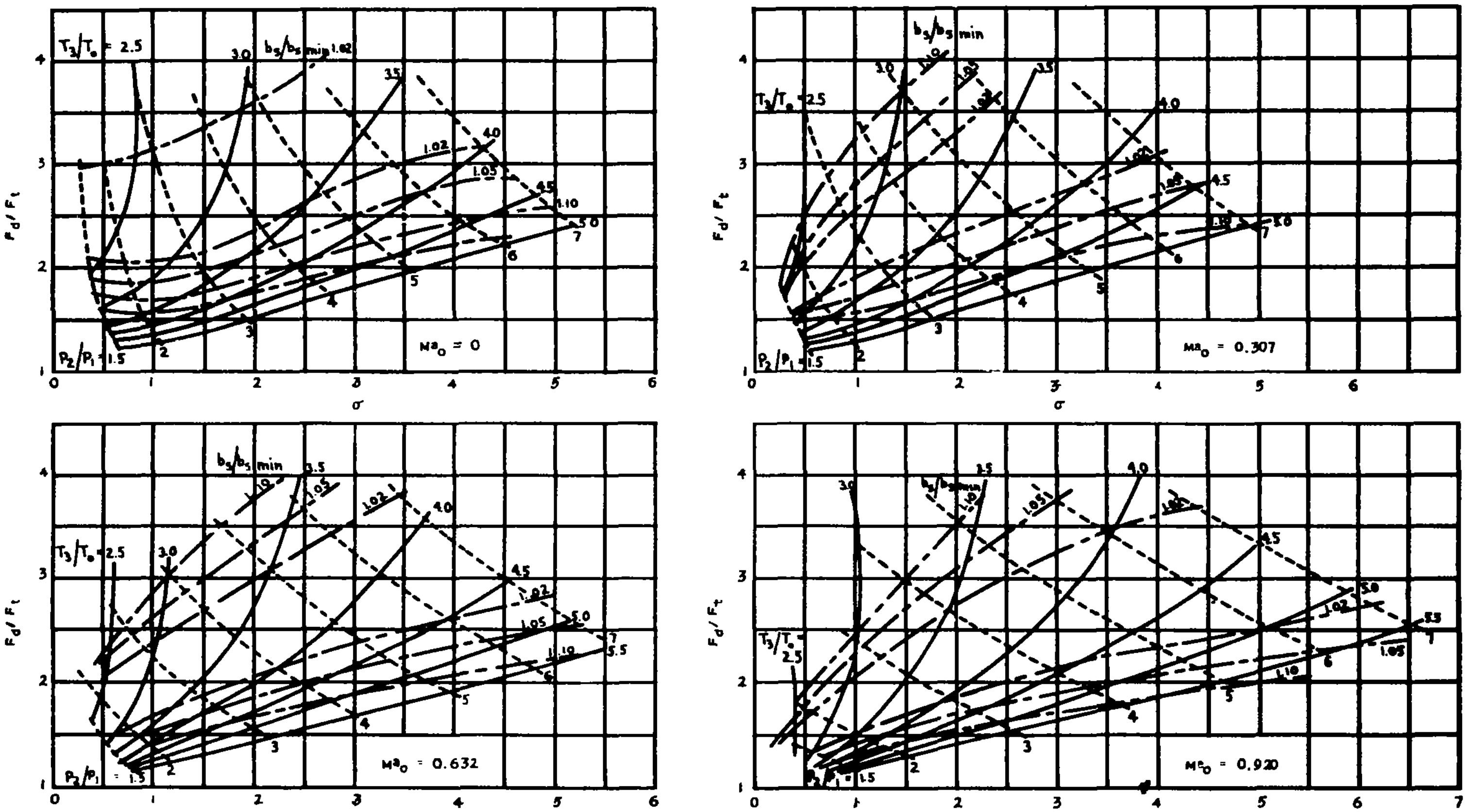

Figure 2. - Ratio of jet-nozzle flow area F_d to turbine-nozzle flow area F_t as function of thrust coefficient $\sigma = S/F_t p_0$ plotted for four Mach numbers $Ma_0 = w_0/20.1\sqrt{T_0}$ calculated on flight speeds (w_0 in m/sec) for various pressure ratios p_2/p_1 and temperature ratios T_3/T_0. In addition, curves of constant increase of fuel consumption above optimum value ($b_S/b_{S\,min}$ = constant) are shown.

Product of compressor and turbine efficiencies $\eta_l\ \eta^*_t = 0.595$;

$\eta_l = 0.85$ $\eta^*_t = 0.70$; $\eta_{st} = 0.90$; $\eta_b = 0.95$; $\mu_t = 0.94$;

$\varphi_d = 0.96$; $p_3 = p_2$.

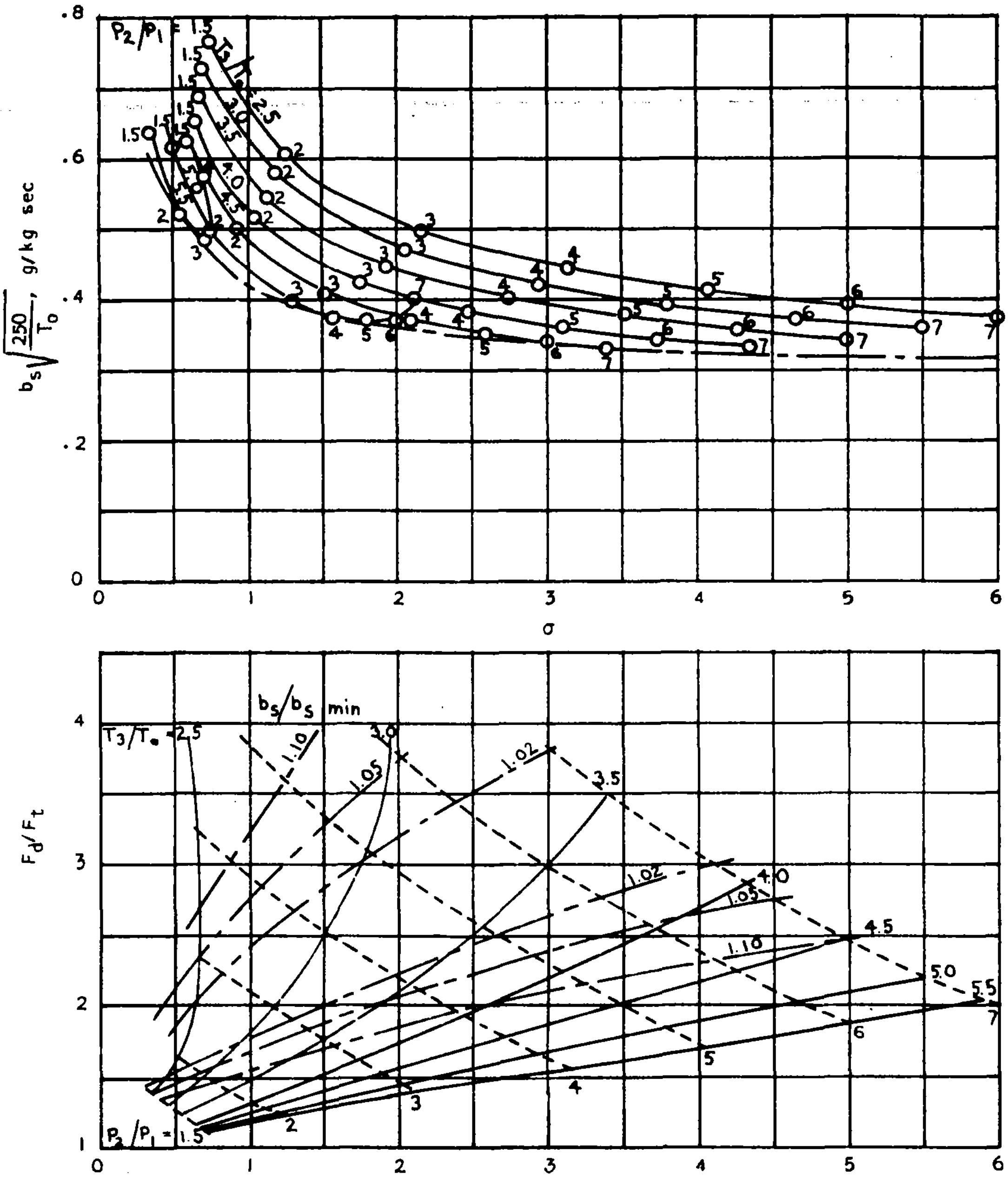

Figure 3. - Index of specific fuel consumption $b_S \sqrt{250/T_o}$ (upper graph) and ratio of jet-nozzle flow area F_d to turbine-nozzle flow area F_t (lower graph) as functions of thrust coefficient $\sigma = S/F_t p_o$ when $Ma_o = w_o/20.1\sqrt{T_o} = 0.632$ (w_o = 200 m/sec at 6 km Ina) for various pressure ratios p_2/p_1 and temperature ratios T_3/T_o.

Product of compressor and turbine efficiencies $\eta_l \eta^*_t = 0.68$; $\eta_l = 0.85$; $\eta^*_t = 0.80$; $\eta_{st} = 0.90$; $\eta_b = 0.95$; $\mu_t = 0.94$; $\varphi_d = 0.96$; $p_3 = p_2$.

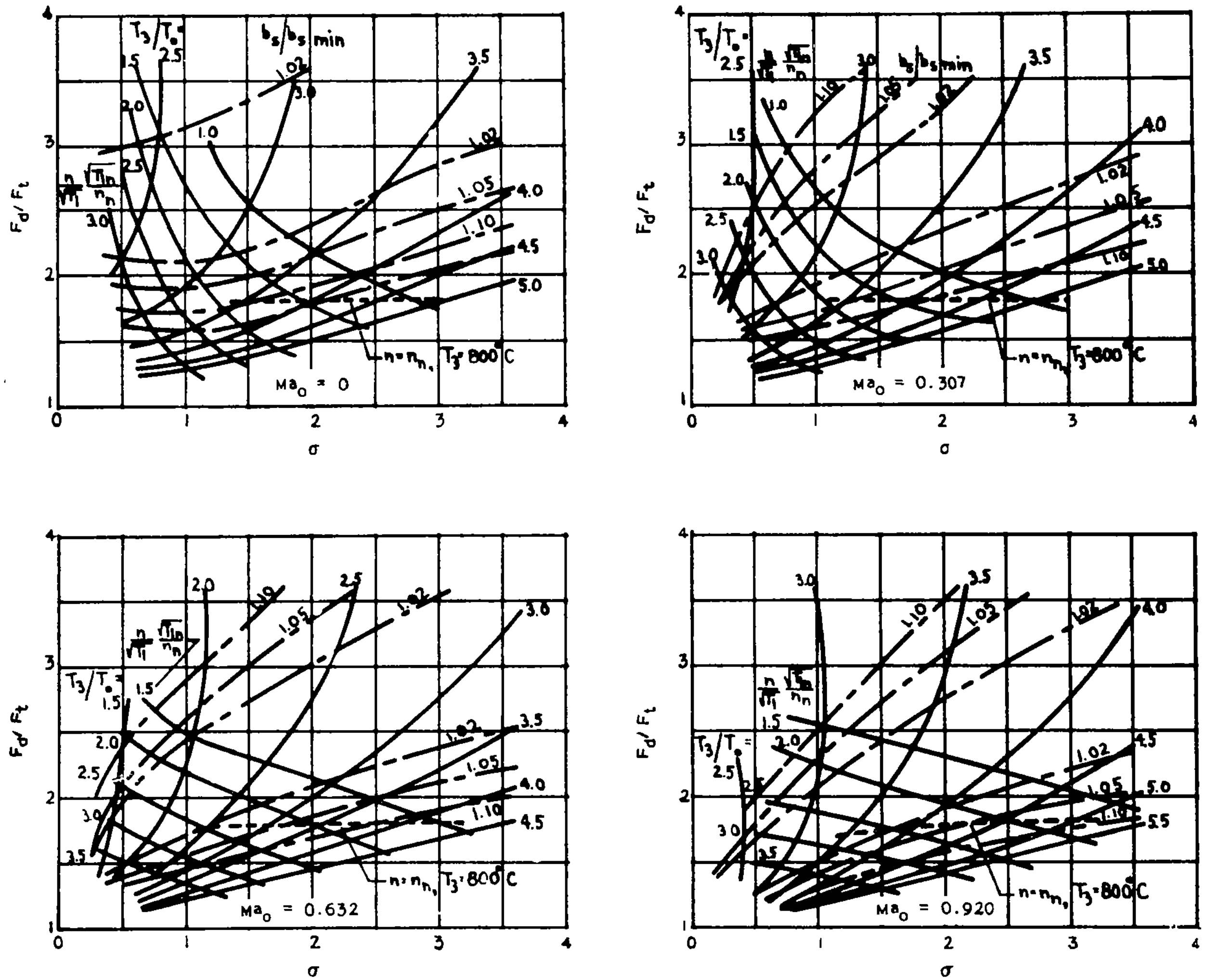

Figure 4. - F_d/F_t as function of $\sigma = S/F_t\rho_0$ plotted for four Mach numbers $Ma_0 = w_0/20.1\sqrt{T_0}$ and various values of T_3/T_0 and $(n/\sqrt{T_1})\sqrt{T_{1n}}/n_n$ for example corresponding to compressor characteristics diagram in figure 2, part II. (n_n and T_{1n} are values at designated point.) Numerical values as in figures 1 and 2.

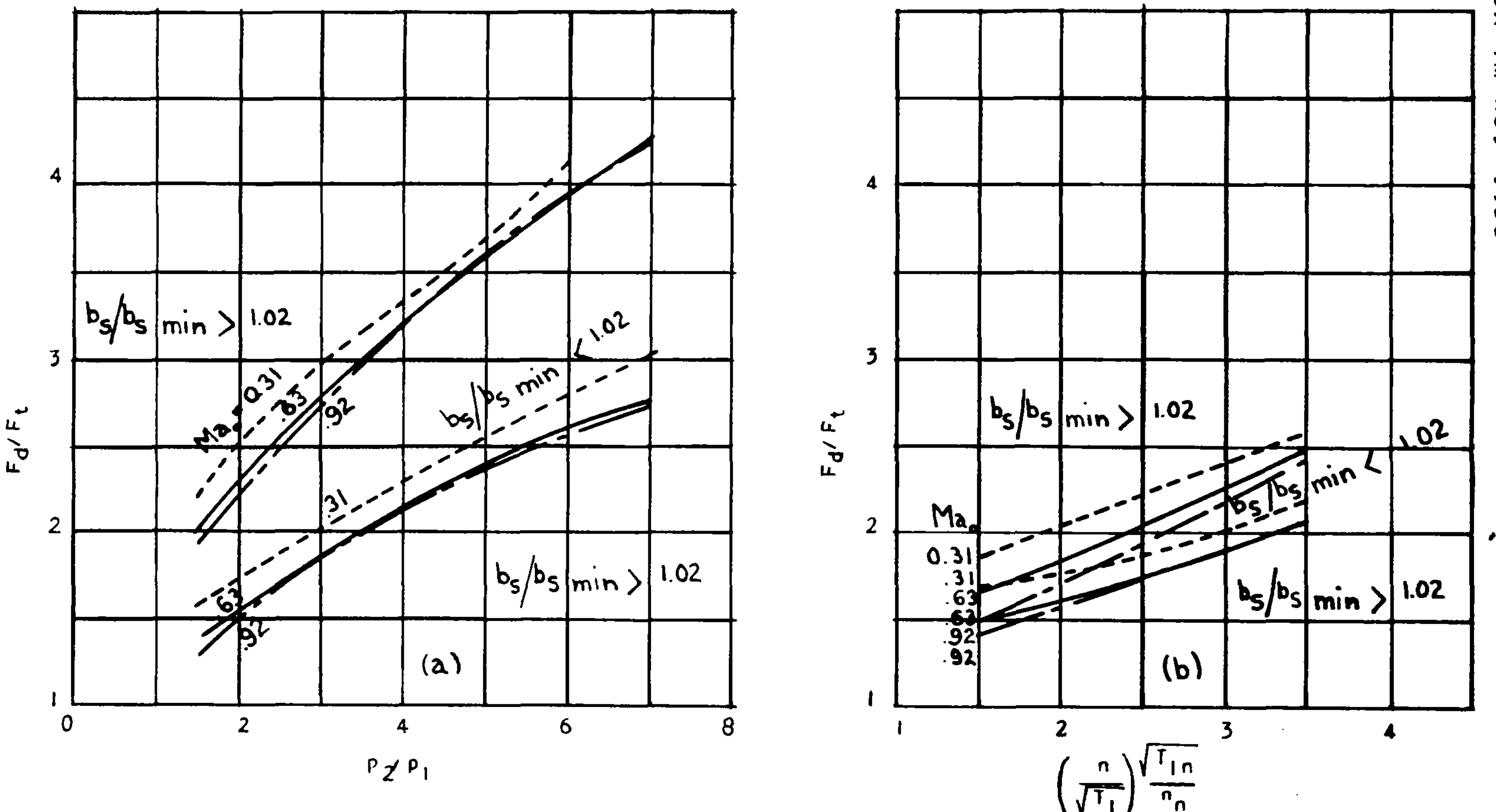

Figure 5. - Ratio of jet-nozzle flow area F_d to turbine-nozzle flow area F_t when b_S/b_{Smin} = 1.02 for various values of $Ma_0 = w_0/20.1\sqrt{T_0}$ dependent on:

(a) pressure ratio p_2/p_1 in accordance with figure 2

(b) quantity $(n/\sqrt{T_1})\sqrt{T_{1n}}/n_n$ for example corresponding to figure 4.

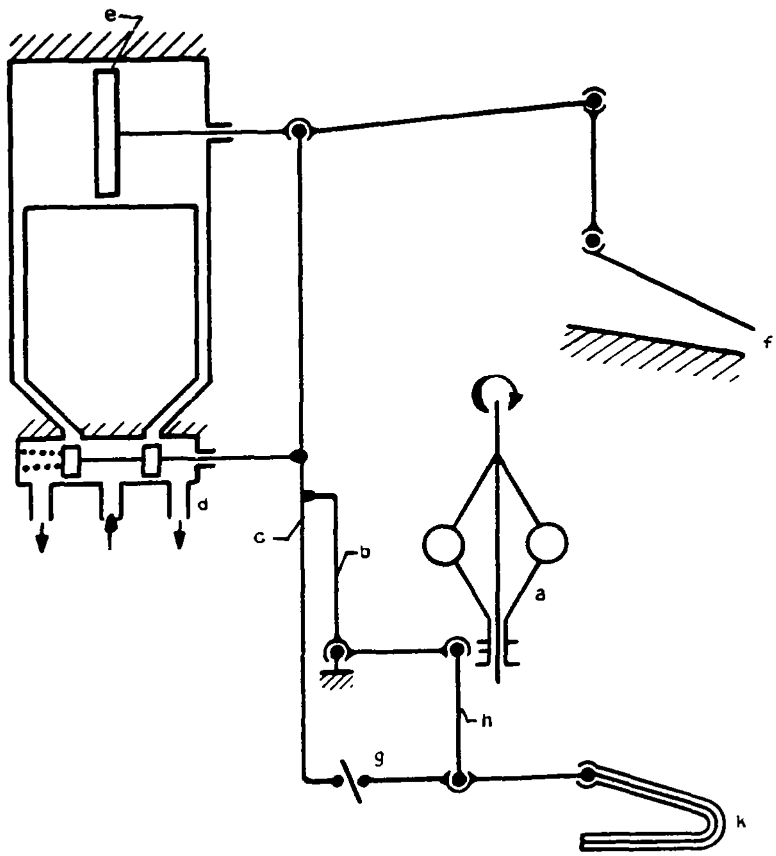

Figure 6. - Diagram of suggested system for control of jet-nozzle flow area of jet engine when pilot's manual control lever is used to select fuel quantity.

Simplifications permissable in many cases:

(1) If T_1 is disregarded, omit k; right-hand pivot of i is fixed

(2) If jet-nozzle flow area is constant in region of variable speed, add adjustable stop for piston e; omit g, h, i, and k.

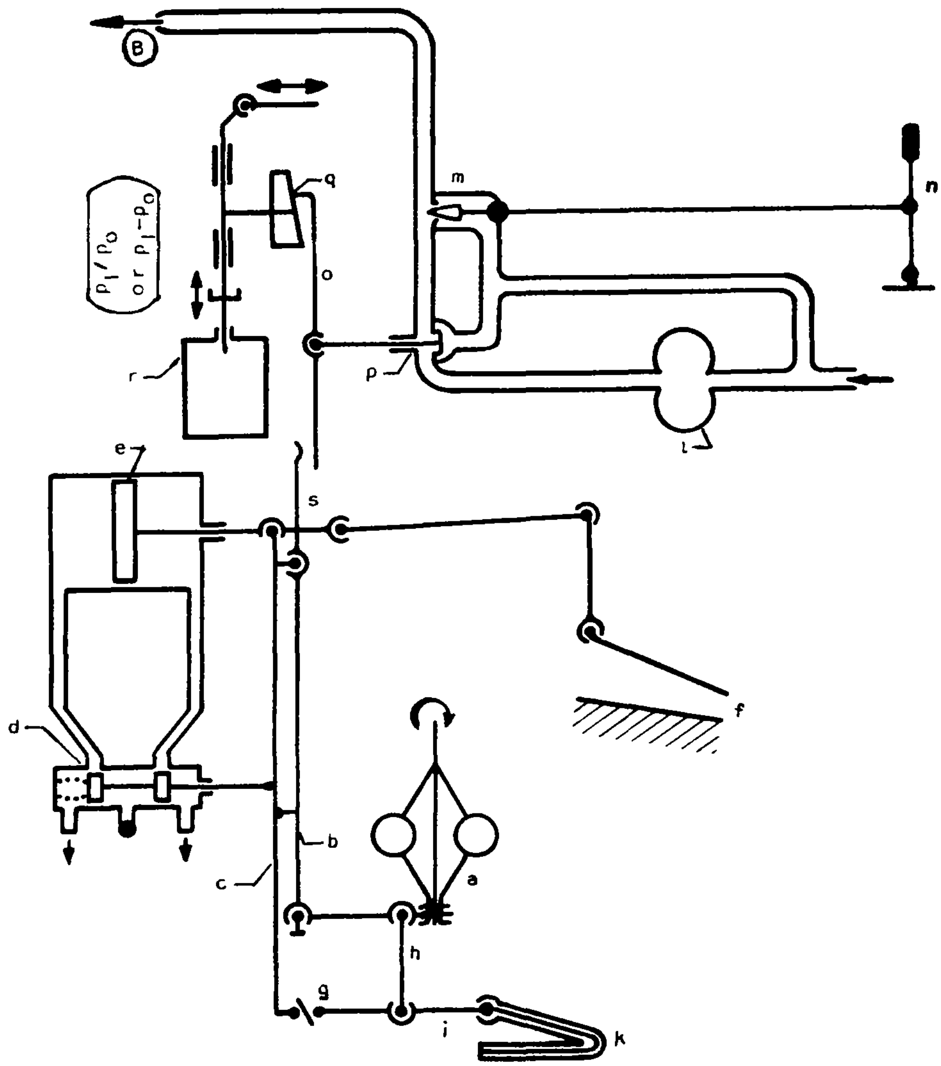

Figure 7. - Diagram of suggested system for control of jet-nozzle flow area of jet engine in combination with limitation of gas temperature in equilibrium condition when pilot's manual control lever n is used to select fuel quantity.

Permissible simplifications in certain cases same as for figure 6.

For limitations of applicability of this design see section IV.

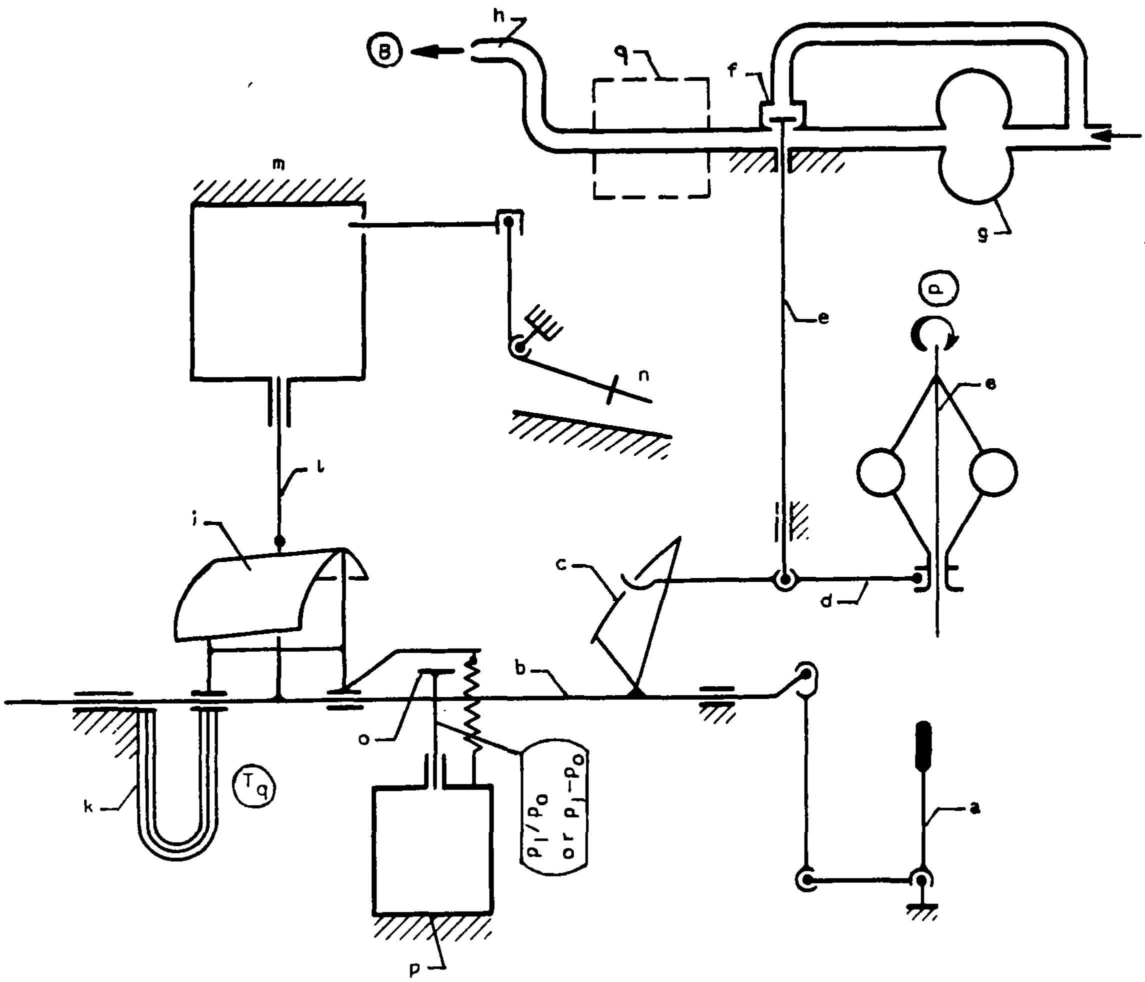

Figure 8. - Diagram of suggested system for controlling jet engine including limitation of gas temperature in equilibrium condition (see text for prerequisites) for case in which speed is selected by pilot's manual control lever.

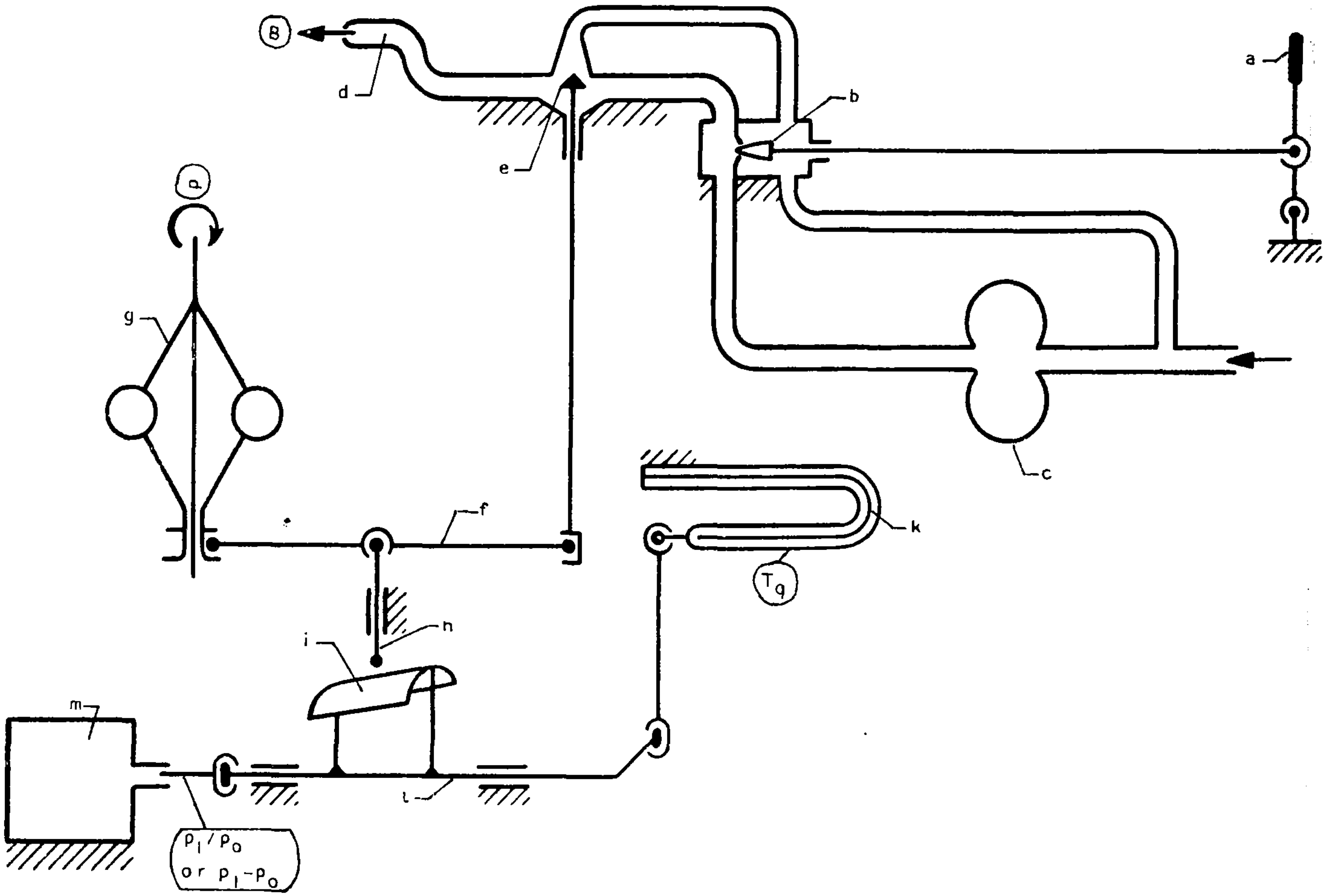

Figure 9. - Diagram of suggested system for controlling jet engine with fixed jet-nozzle flow area. See page 17 for additional simplifications. Restrictions on applicability of system presented here for limitation of fuel quantity will be found in section V.